# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3484



## ON SPECTRAL ANALYSIS OF RUNWAY ROUGHNESS AND LOADS DEVELOPED DURING TAXIING

By John C. Houbolt, James H. Walls, and Robert F. Smiley

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
July 1955

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3484

# ON SPECTRAL ANALYSIS OF RUNWAY ROUGHNESS AND LOADS DEVELOPED DURING TAXIING

By John C. Houbolt, James H. Walls, and Robert F. Smiley

## SUMMARY

The application of the techniques of generalized harmonic analysis to the airplane taxiing problem is considered rather briefly in this paper. Some previous results on runway roughness are reviewed, and some results obtained from taxiing tests of a large airplane are given.

It is indicated that an extrapolation by elementary means of results from low taxiing velocities to higher taxiing velocities would lead to conservative results. Oleo-strut friction is shown to be a very important factor in the taxiing problem. With regard to the load-prediction phase of taxiing loads by spectral techniques, much additional work is required, especially with respect to the treatment of the transfer functions.

## INTRODUCTION

The purpose of this paper is to review some previous runway-roughness measurements and to present some results obtained from taxiing tests of a Boeing B-29 airplane. Besides the results themselves, the chief concern is a preliminary evaluation of how well the techniques of generalized harmonic analysis apply in the analysis of the taxiing problems. There is no intent in the paper to make a comprehensive study of the problem or even to evaluate in detail some of the points covered. This paper is to be regarded as being introductory in nature.

## RUNWAY-ROUGHNESS STUDIES

A brief review of an earlier runway-roughness study is given in this section. Measurements of elevation were made by means of a surveyor's level and rod on two runways at Langley Field, Va. The spacing of the measurements was taken as 2 feet. These measurements and the power spectra of roughness obtained from them have been previously published in reference 1. The power spectra are reproduced in figure 1 where the ordinate $\Phi_h(\Omega)$ is the power spectrum of runway elevation h and the abscissa $\Omega$ is a spacial frequency which is inversely related to the length L of the harmonic components as indicated in the figure. The curve labeled "smooth" applies to one of the Langley runways in routine use. The curve labeled "rough" applies to a runway which is now used only for parking.

From these results three significant points may be drawn: (1) The use of power-spectral analysis seems to be a very concise way of presenting runway characteristics and gives at a glance the manner in which the roughness is distributed to the various frequency components. (2) A means is suggested for establishing a criterion for judging the severity of runway roughness. Thus, it is conceivable that, by compiling the spectra of many different satisfactory runways, a spectrum may be established within whose limits all new runways must be built or all old runways maintained in order to insure satisfactory operation. And (3) as an extension of the second point, a "design spectrum" might also conceivably be established which provides the basis for a rational requirement in the design for taxi loads.

It is realized at present that the question of whether a runway is rough is largely a subjective one; it depends on pilot interpretation, his experience, what type of operations are being performed, and other considerations. From the information that could be gathered, it is judged that the rough runway dealt with in reference 1 is a borderline case. Thus, tentatively the experimental spectrum for this runway might be regarded as an upper limit of acceptable roughness, or as a lower limit of runways which are too rough.

## LOAD PREDICTION AND RESULTS OF TAXIING STUDIES

The problem of predicting loads in an airplane from spectra of roughness is now considered. For the airplane with pneumatic tires, nonlinear struts, and many degrees of freedom, the problem is extremely difficult; in fact, it is not known whether a solution is possible. However, the remainder of this paper does present a few observations pertinent to a solution of this problem which have been gathered largely from taxi tests with a Boeing B-29 airplane. By way of introduction, consider what elementary theory would predict. As a first approximation, the runway-roughness spectrum may be expressed by a simple expression of the form $\Phi_h(\Omega) = C/\Omega^2$, where C is a constant. In terms of the frequency argument $\omega = V\Omega$, where $\omega$ is frequency in radians per second and V is velocity, the roughness spectrum would be $\Phi_h(\omega) = CV/\omega^2$ (since $\Phi_h(\Omega) = V\Phi_h(\omega)$). If a linear system is assumed, then the following input-output relation applies:

$$\Phi_o(\omega) = T^2(\omega)\Phi_h(\omega)$$

where $\Phi_o(\omega)$ is the output spectrum and $T(\omega)$ is the amplitude of the frequency-response function. With the previous approximate input expression, the output would be

$$\Phi_o(\omega) = V \frac{CT^2(\omega)}{\omega^2}$$

Now, if the further assumption is made that $T$ is independent of airplane velocity when expressed in terms of the frequency argument $\omega$, it is seen that the output spectrum should be linearly proportional to $V$. This suggests that the mean-square output, which is the area under the output spectrum, is proportional to $V$.

This relation was tested by means of the B-29 taxi tests and the results are shown in figure 2, where $\sigma_a{}^2$ is the mean-square value of center-of-gravity vertical acceleration. It is seen that the results are surprisingly linear for the lower velocities. There is, however, a marked dropoff in the mean-square acceleration for high velocities; an explanation for this is offered in the subsequent discussion.

Next, the distribution of mean-square acceleration to the various frequency components is considered. Figure 3 shows the B-29 output spectra, in terms of the spectrum of center-of-gravity vertical acceleration, plotted as a function of frequency $\omega$ in radians per second. Curves are shown for three different velocities. First, note the rather pronounced peaks in the spectra. These peaks may be identified with certain natural frequencies. The first peak is associated with the vibration of the airplane on its tires; the second, with fundamental wing bending; and the third, with fuselage bending. Next, note that at the higher frequencies there is an orderly increase in the spectra height with velocity, consistent with the result derived on an elementary basis. At the lower frequencies, however, where there is the most power, there is first an increase and then a decrease as the velocity increases. As was previously mentioned, the areas under these curves equal the mean-square accelerations. It can, thus, be seen that the area would not increase linearly with velocity; but more specifically it can be seen that the departure from linearity is due largely to the dropoff of the spectra at high velocities in the lower range of frequency, where the roughness is most severe.

An explanation of why this dropoff occurred can be made by examining the behavior of the main oleo struts, which is shown in figure 4. This figure presents reproduced oscillograph traces of oleo-strut motion which show two important points: (1) At 10 mph, there is no strut motion; and (2) at other velocities, strut motion is only in the form of random step functions, the number and severity of these step functions increasing as the velocity increases. Both these points indicate the presence of a very sizable friction force in the struts. In fact, at 10 mph, the taxiing loads evidently never exceeded the friction force; and, therefore, the airplane behaved like a flexible structure on elastic tires only. At higher taxiing speeds the strut releases momentarily and then seizes as the taxiing loads occasionally exceed the friction force, and the number of such occurrences increases with velocity as might be expected. This inherent load-limiting action seems to account for the dropoff in the output spectra at the higher velocities. To see this erratic behavior take place, however, is somewhat disconcerting, since it appears that such factors have to be included in the treatment of the problem.

In the treatment of this problem by spectral techniques, the determination of the frequency response or transfer function is of primary interest. It has been suggested that perhaps the frequency-response function of the airplane could be deduced from the response that is obtained by taxiing over rectangular bumps, thereby obviating all the assumptions and restrictions that would have to be made in attempting to derive these functions analytically. Therefore, some taxiing runs over rectangular planks were included in the B-29 taxi tests. Figure 5 shows three of the time histories of center-of-gravity acceleration that were obtained. It is noted that these curves resemble the damped 10 cps sine wave which is shown also for comparison. This 10 cps frequency is very much higher than the predominating characteristic frequencies that are present in the output spectra of figure 3, which were on the order of 2 to 3 cps. The impulsive loads received from the planks evidently excite a very high frequency component which completely dominates the lower frequencies of concern in continuous roughness studies. In addition, there was a very pronounced oleo movement in these tests. Thus, not only are different frequencies excited but also the system behaves differently than it does in the normal taxiing operations. There is, therefore, no point in trying to derive the frequency-response functions from these impulse responses, since there is essentially no low frequency power coming through. The conclusion drawn is that presumably a more appropriate type of test would be to taxi over a corrugated surface having long wavelengths.

The final aspect in this paper deals with the computation of the frequency response or transfer function. As yet it is not known whether it is possible to pursue the course of action where an equivalent linear system is found which will yield results characteristic of the actual system, or whether it is necessary to go to a more involved nonlinear treatment. Many of the remarks made thus far concerning the several structural degrees of freedom and the erratic behavior of the oleo as brought about by strut friction - not to mention the inherent nonlinear characteristics - suggest some of the factors that undoubtedly have to be included in this consideration. As an example of another factor which has to be included, figure 6 presents theoretically derived transfer functions for the case where the airplane is considered rigid and the landing struts are replaced by linear undamped springs. The point to note is that the transfer function at 80 mph is slightly different than at 10 mph, thereby indicating a slight velocity dependence, which is contrary to the assumption made in the elementary consideration at the beginning of this paper. Thus, velocity is another factor which must be considered. The manner in which velocity enters is connected with the bumps and valleys of the curves in figure 6. The first two peaks are associated with a structural type of resonance; the other peaks, however, are associated with a geometric type of resonance. These later peaks correspond roughly to the condition where the wavelengths of the ground roughness are direct multiples of the distance between the main and nose landing gears. For these conditions, both main and nose landing gears rise and fall together; hence, the individual effects of the two gears on the center-of-gravity acceleration are additive. The later valleys on the curves correspond roughly to those ground wavelength conditions where the motions of the two gears are the most out of phase, such that the main gear is rising when the nose gear is falling. Hence, one gear tends to produce positive center-of-gravity acceleration, while the other one tends to produce negative acceleration - the net center-of-gravity acceleration being the difference of these two accelerations as compared to the sum for the case where the two gear motions are in phase.

## CONCLUSIONS

From an investigation of runway roughness and loads developed during taxiing of a large flexible airplane, the following conclusions are presented:

1. The use of spectral techniques seems to be a rather concise way of presenting the characteristics of runway roughness.

2. An extrapolation by elementary means of results from low taxiing velocities to higher taxiing velocities would lead to conservative results.

3. Oleo-strut friction is an important factor in the behavior of airplanes while taxiing.

4. With regard to the load-prediction phase of taxiing loads by spectral techniques, much additional work is required, especially with respect to the treatment of the transfer function.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 12, 1955.

## REFERENCE

1. Walls, James H., Houbolt, John C., and Press, Harry: Some Measurements and Power Spectra of Runway Roughness. NACA TN 3305, 1954.

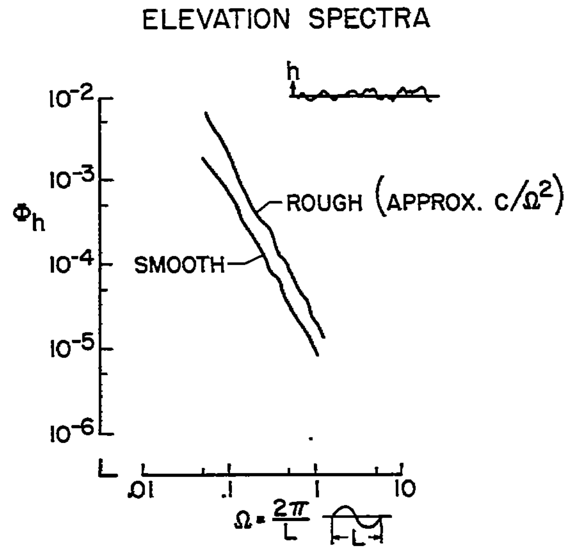


Figure 1

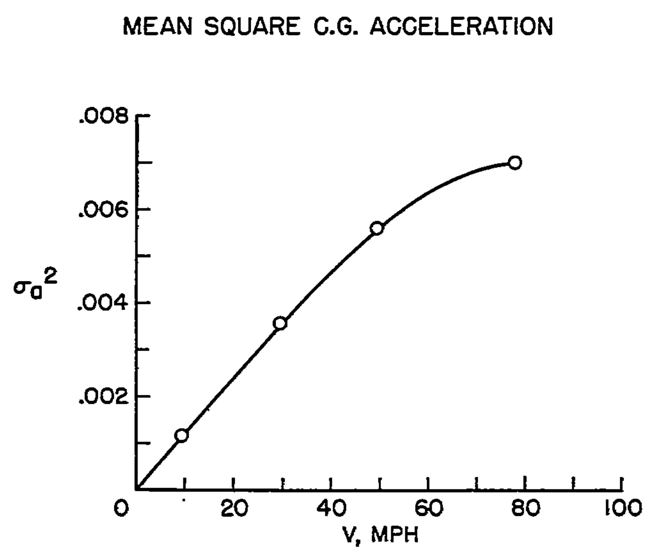


Figure 2

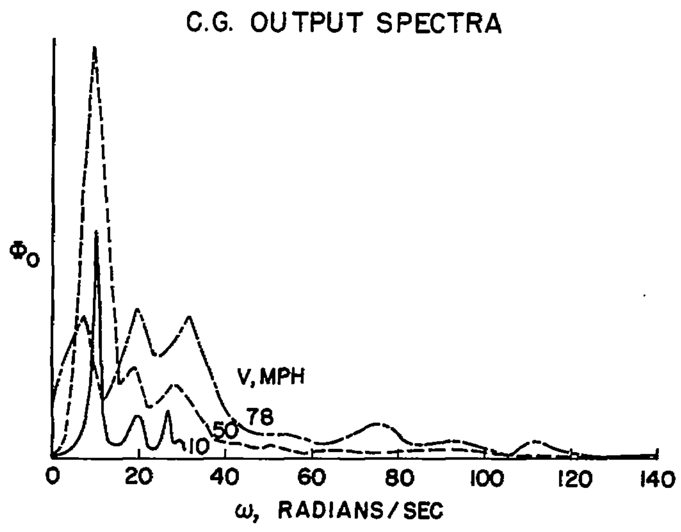


Figure 3

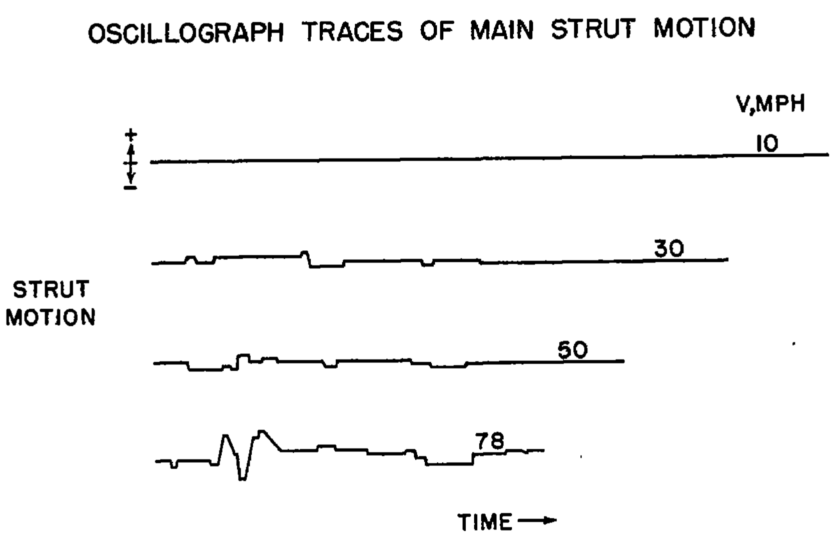


Figure 4

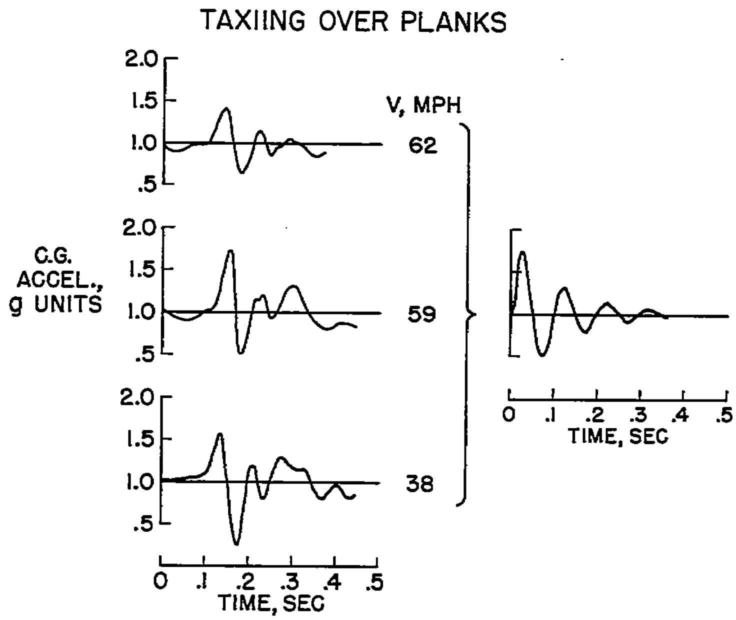


Figure 5

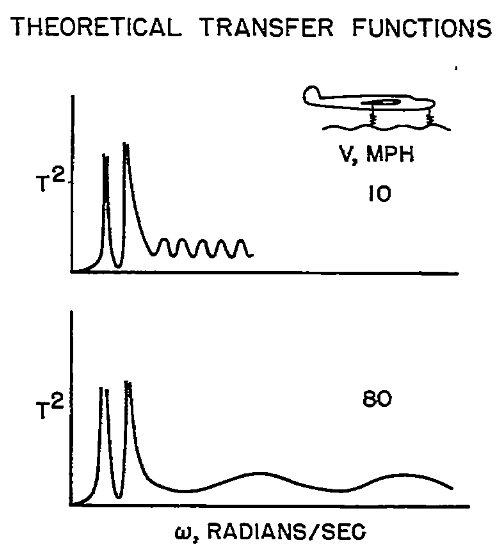


Figure 6

NACA - Langley Field, Va.